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Considerations for Optimum Siting of NEXRAD to Detect Convective Phenomena Hazardous to Terminal Air Navigation (PART 1)

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Final Report

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16. Abstract

The aviation community has been concerned for some time about the number of aircraft accidents during terminal flight in which weather has been identified as the cause or a contributing factor. The next generation weather radar (NEXRAD), for which final specifications are being worked out on a multi-service basis, offers the possibility of dedicated and detailed surveillance of hazardous weather in the terminal airspace. This report outlines considerations for choosing a site for a NEXRAD installation to fulfill this role in an optimum manner. It is shown that the detection of low level wind shear without precipitation imposes the most severe constraints on NEXRAD siting. Three general siting areas are considered: (1) within the airport area, (2) within the terminal area, but outside the airport area, (3) outside the terminal area. When a single NEXRAD radar must cover all hazardous phenomena over the terminal area, siting within the airport area appears to be the best choice. Under certain conditions, a case exists for siting the NEXRAD outside the terminal area.

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METRIC CONVERSION FACTORS

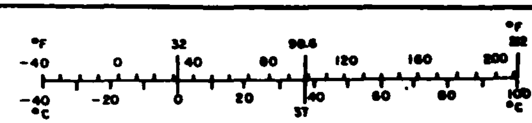
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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CONSIDERATIONS FOR OPTIMUM SITING OF NEXRAD TO DETECT CONVECTIVE PHENOMENA HAZARDOUS TO TERMINAL AIR NAVIGATION

P.R. Mahapatra, D.S. Zrnic', and R.J. Doviak

1. Introduction

Reliable detection of hazardous weather phenomena near terminals has been a matter of continuing interest for the Federal Aviation Administration. A number of reports [1-11] in the last decade have established a strong link between atmospheric convection and aircraft accidents. Also, severe weather phenomena such as thunderstorms have been found to be the largest single cause of air traffic delays in excess of 30 minutes in recent years[12]. There is thus a growing need to incorporate into the terminal air traffic control system an improved capability to detect and identify elements of weather which are hazardous to aviation.

An aircraft would naturally respond to any disturbances occurring in the air mass in which it flies. However, the hazard potential of atmospheric disturbances is highest during the initial and terminal phases of an aircraft flight. This is so because during takeoff and landing an aircraft has very little airspeed and altitude to spare, and since the aircraft is in a high-lift configuration, it is more vulnerable to rapid changes in airspeed than it is under cruise conditions. Also, the effect of disturbances is greater at low altitude where the air density is larger.

The problem of terminal area hazard detection is rendered rather complex by the fact that threats to flight safety come from a number of dissimilar atmospheric processes associated with thunderstorms such as tornadoes, downdrafts, low-level wind shear, hailstorms, etc., affecting air flight in basically different ways. A successful hazard warning system must be capable of observing as many of these diverse phenomena as possible. To achieve economy in installation and operation, a maximum amount of common equipment should be used for the various tasks.

Detailed specifications and system configurations are being currently worked out for a multi-service next generation weather radar system (NEXRAD) based on the pulsed-Doppler principle and employing advanced techniques for signal processing and display. Federal Aviation Administration, which is a participant in the NEXRAD project, is interested in using this system for improving the safety of terminal area air navigation and has initiated agreements and contracts with National Severe Storms Laboratory (NSSL), Norman, Oklahoma, to study many aspects

of thunderstorms. One study includes generation of data for evolving system specifications such as scan rate and scan pattern, and another involves the determination of an optimum position of the NEXRAD system relative to the airport area -- the so-called "siting" problem.

This paper deals with the factors that must be considered to determine an optimum siting for the next generation weather radar system from the point of view of detection of hazardous weather in air terminal areas.

2. Weather Environment in Terminal Areas

Several atmospheric phenomena affect air safety in terminal areas. The most familiar and easily observable among these are thunderstorms with heavy precipitation and often accompanied by strong winds. Turbulence, reduced visibility and improper combustion (partial extinction) in jet engines, due to excessive water in intake air, are major aviation hazards associated with thunderstorms.

Another class of phenomena of serious concern in terminal navigation consists of low-level wind shear and gust fronts[13-16]. Precipitation may or may not be present. Gust fronts often are associated with, and stay attached to, the thunderstorms that cause them. However, it is not uncommon to find gust fronts detaching themselves and propagating independently over considerable distances, often as far as 30 to 50 km beyond the storm cell[13]. A scenario depicting the hazard posed by low-level wind shear to aircraft in terminal maneuver (landing or takeoff) is shown in Fig. 1. Cold air downflow from a thunderstorm has a very well-defined boundary with the warm air inflow, causing a sharp shear layer to form at the interface. A low-flying aircraft would experience a sudden jump in airspeed while passing through the shear layer. This would cause large departures from the nominal flight path, or even instabilities, without prompt corrective pilot input. If this occurs too close to the ground, such perturbations can be fatal. The importance of wind shear as a hazard factor in terminal areas is borne out by the large number of recent studies based on both radar remote sensing[17-20] as well as direct airborne measurement[21,22]. Although methods have been suggested to minimize the hazardous effects of wind shear by modifying the flight procedure and/or flight instrumentation[23,24], these methods are still experimental and are likely to be limited in application because of the limited airspeed margin (airspeed in excess of local stall speed) available when the aircraft is close to landing or takeoff. The best approach, at present, seems to be to detect any hazardous wind shear along runways and glideslopes and warn the pilot so that he may avoid the hazards or remain alert for corrective action.

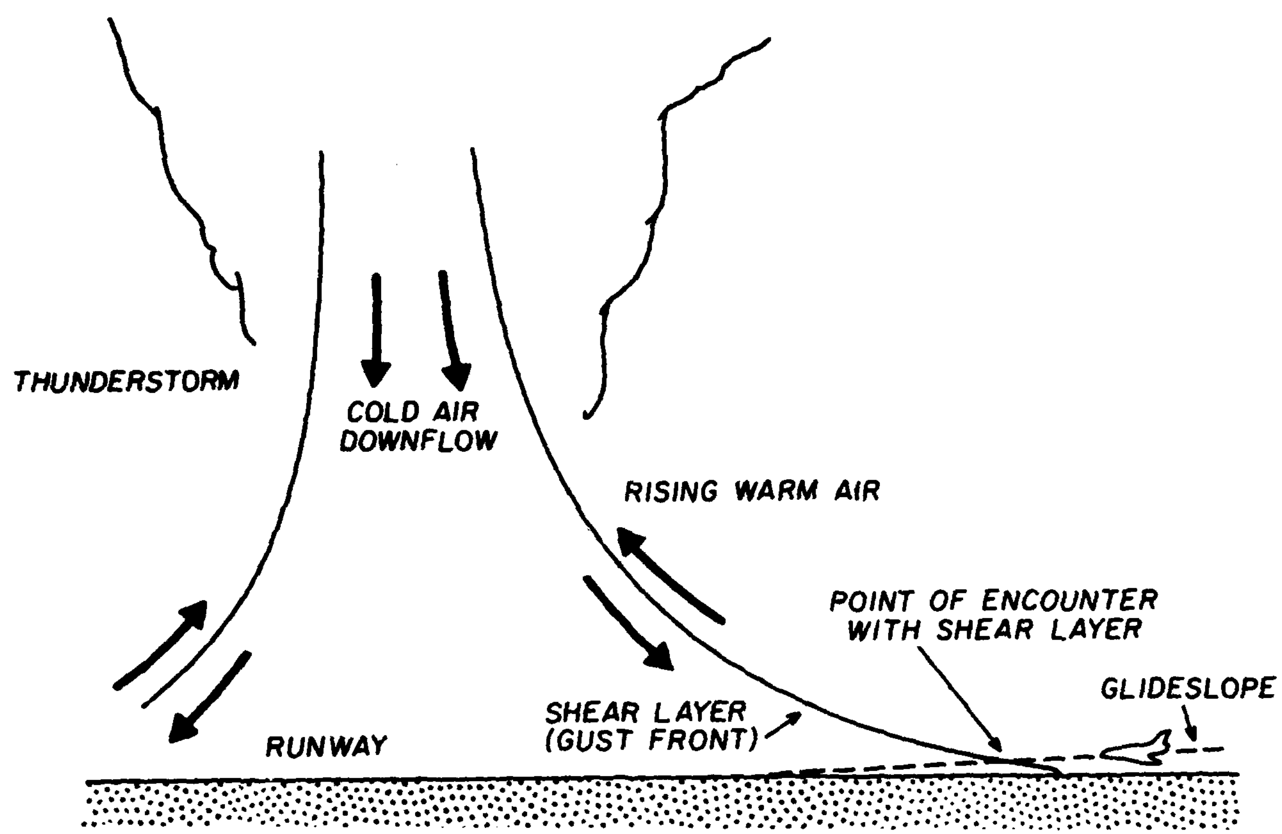

Figure 1   Scenario depicting encounter of aircraft with low-level wind shear.

An atmospheric turbulence phenomenon of great interest to terminal area navigation is the shedding of powerful wake vortices by large jet aircraft. These vortices are often strong enough to affect the flight of following aircraft, especially the smaller ones, within the wake region. This has led to minimum separation standards between aircraft taking off or landing. A reduction in this separation would increase landing rates at airports, reduce aircraft delays, and lower operating costs and fuel expenditures.

Such a reduction is possible because wake vortex turbulence is often dissipated faster or deflected from the flight plane by a variety of wind and temperature conditions. Thus, spacing between aircraft may be altered in each case depending on the force and location of the wake as actually observed. The needed observations can, in principle, be conducted by weather radars[17,25,26], although wake vortex turbulence is not a phenomenon of weather origin.

3. Next Generation Weather Radars

Weather radars operate essentially by transmitting bursts of microwave energy and detecting the energy backscattered by the weather phenomena. In order to return detectable amounts of energy, weather phenomena must contain sufficient numbers of scattering agents of appreciable size. These scatterers are called "tracers" because they help trace the motion of the air mass which carries them. In severe weather phenomena, solid or liquid particles such as hail or raindrops, usually serve as tracers. When these particles are absent, and the air is optically clear, small-scale (several centimeters) pockets of turbulence containing refractive index gradients act as tracers. In general, the latter type of tracers return less signal than the former. It is thus more difficult to observe clear-air weather phenomena than to observe precipitation.

At present, routine radar observation of weather in the U.S., conducted by the National Weather Service using the WSR-57 radar, relies almost entirely on reflectivity measurement, i.e., the estimation of power returned from scatterers in individual radar resolution cells weighted by certain radar parameters such as antenna pattern, pulse shape, receiver response, etc. The underlying assumption here is that the higher the echo strength, the higher the water content and, hence, higher is the severity of a weather phenomenon. However, with increasing demands on weather radars to monitor different types of phenomena and/or observe more attributes and details of the more familiar types, it is becoming clear that

reflectivity measurement alone is not enough. Thus, future weather radars must be "Dopplerized," i.e., provided with capability to process echo returns coherently from pulse to pulse so as to estimate the radial velocity of the tracers (relative to the radar site) contained in different resolution volumes.

Radar observation of weather phenomena differs substantially from observation of point targets such as aircraft. The latter type causes a Doppler shift which is essentially a single frequency, while the former generates an ensemble of frequencies, caused by the motion of numerous individual scatterers within the resolution volume. Thus, in weather observation, one deals with a "Doppler spectrum" (Fig. 2) instead of Doppler frequency, and estimates the moments of the spectrum that are related to the attributes of the weather process. The zeroth moment, or the area under the power spectrum curve, is a measure of reflectivity indicative of the intensity of precipitation in the resolution cell. The mean Doppler frequency, the first moment of the power spectrum (about the power spectral density axis) normalized with respect to the zeroth, indicates the mean radial velocity of the air within the resolution cell. The square root of the normalized second moment of the Doppler spectrum, usually referred to as "spectrum width", corresponds to the level of turbulence and shear within the radar resolution cell.

Moments of higher orders can be defined, but they not only progressively lose correspondence with reality, but are increasingly difficult to evaluate and have diminishing accuracies. For almost all applications, it will suffice to measure and display the first three spectral moments.

Coherent radar processing to extract Doppler information requires that time series data obtained from the receiver be in complex form, containing both the amplitude and phase of the echo return from each resolution cell. Also, coherent processing requires a much higher stability of transmitter and local oscillator frequency (phase) than is necessary for incoherent processing. These special features are reflected in the block diagram (Fig. 3) of a typical Doppler weather radar. The NEXRAD system, for which specifications are being worked out and design studies are in progress, is likely to be a variant of the system shown in Fig. 3.

There are two basic methods for spectral moment computation: the spectral or Fourier transform method and the autocovariance or pulse-pair method. In the former, calculations are performed in the frequency or spectral domain, whereas in the latter they are carried out in the time domain. The formulae used for moment estimation are given elsewhere[27]. The estimation of moments in the spectral domain is conceptually straightforward; its chief advantage associates with a more

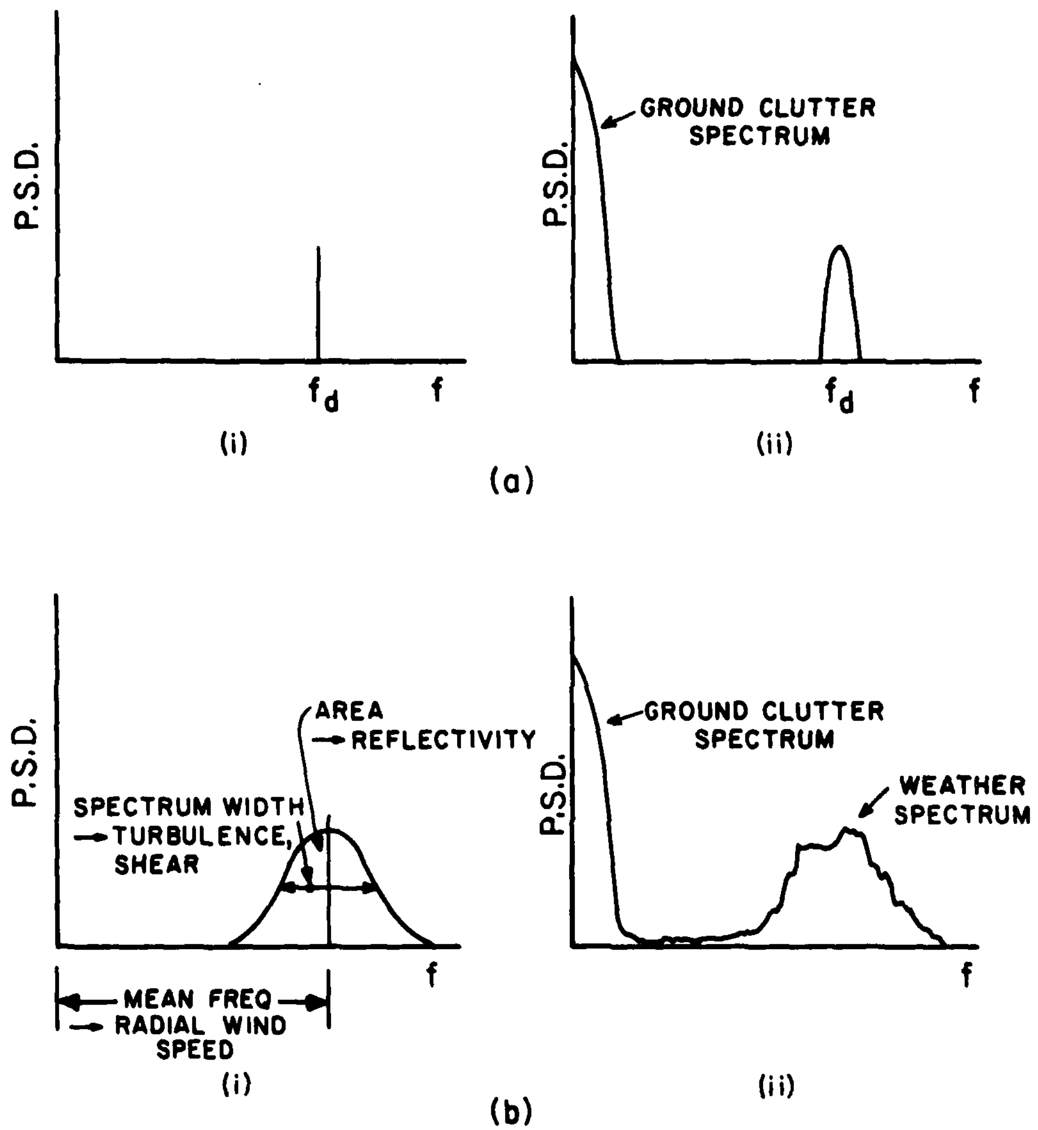

Figure 2(a) *Doppler frequency shift by point target: (i) a moving point target ideally produces a spectrum with zero width, (ii) actual spectrum has finite width and may be accompanied by a ground clutter spectrum component.* f_d = *Doppler shift due to target motion.*

(b) *Doppler spectra of distributed targets, e.g., weather (i) ideal, showing the three moments and their significance (ii) actual, showing distortions and ground clutter contamination.* *(*f = *Doppler shift,* P.S.D. = *Power Spectral Density).*

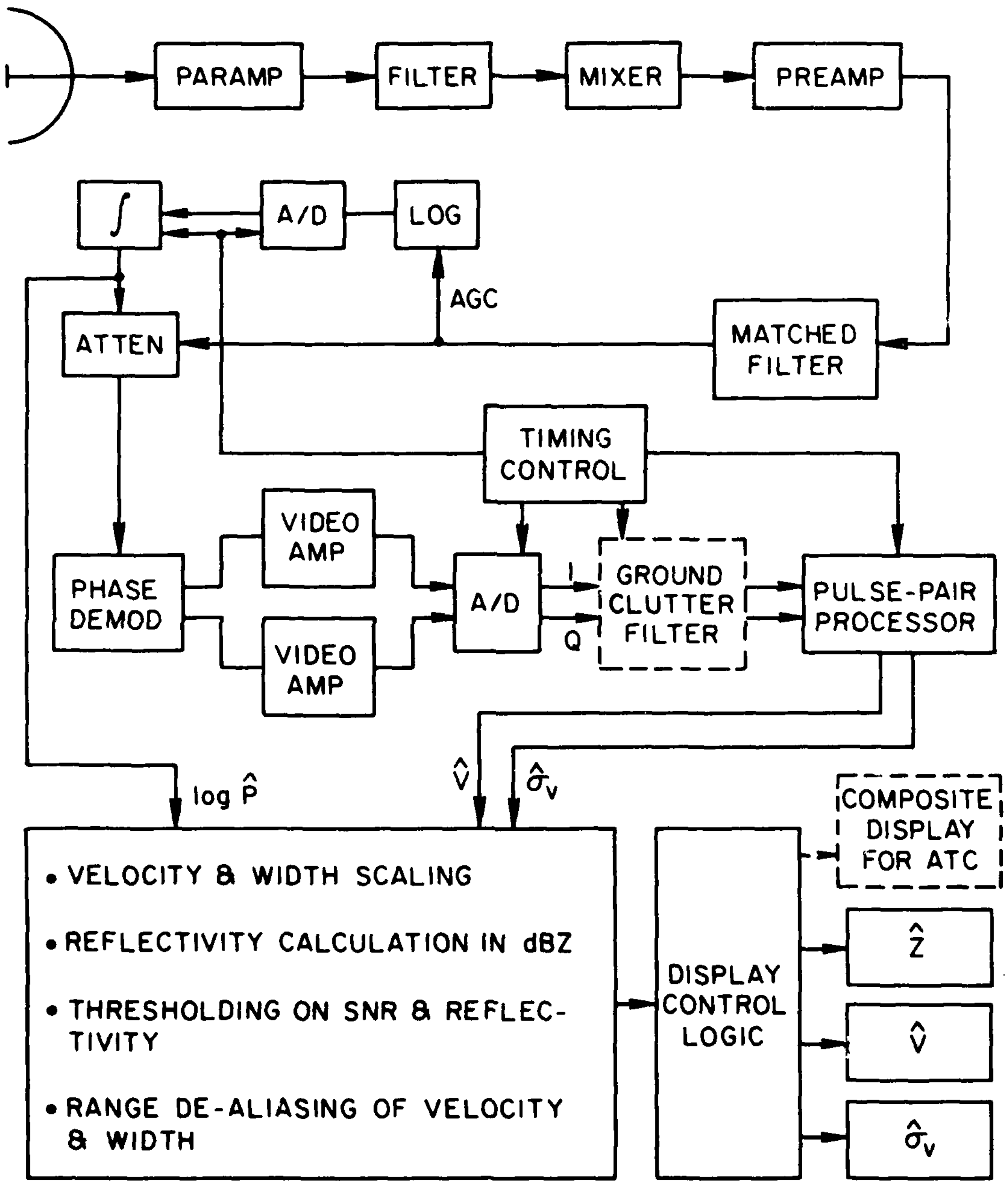

Figure 3 Schematic of a Doppler weather radar receiver.

familiar and easier interpretation of echoes that produce multimodal spectra, i.e., spectra with multiple peaks. Such complex spectra can be produced when weather signals are mixed with echoes from other interfering targets, like aircraft and ground clutter, that may be in the same resolution cell or other cells at the same range. Weather phenomena occurring at a cell different from the one under observation, but at the same range, also constitute interference. The pulse-pair method in contrast, is effective only when spectra are nearly unimodal, as in Fig. 2(b)(i), but offers the advantage of much lower complexity of computation, permitting efficient real-time implementation at an affordable price.

The final specifications of the NEXRAD system are yet to be worked out. However, in order to study the siting problem, a set of baseline characteristics, as given in Table I, may be assumed[28]. It is generally believed that these parameters are close to optimum for an operational Doppler weather radar.

After the three spectral moments are computed for all the resolution cells covered by a scan, they may be displayed on separate color/black-and-white cathode-ray tube displays with color codes/shades of grey representing various quantized levels. Alternatively, features from each of the three moment fields may be combined on a single display. Such a composite display may delineate the hazardous areas with a possible option of color coding hazard types. This holds potential for terminal area radars since it adds the least to the already overcrowded display panels aiding air traffic controllers.

4. Definition of the Siting Problem

Terminal area is defined as an area of radius 30 nautical miles (56 kilometers) around the airport's runway complex. The siting problem is stated as[28]: "Where, and for what reasons, should a single Doppler weather radar be sited within the area identified as the 'terminal area' such that optimum identification, measurement and tracking of those convective attributes termed 'hazards' can be accomplished from the surface to 20,000 feet above MSL."

5. Siting Criteria

In deciding a site for locating a radar of the NEXRAD type to detect convective phenomena hazardous to terminal area navigation, the following criteria must be considered:

Table I

Typical Characteristics of a Pulsed Doppler Weather Radar

Characteristics	Specification or Specification Range
Wave Length	10 centimeters
Beam width	0.75 to 1.25 degrees
Number of beams	1 or 2
Pulse widths	0.15 km to 0.45 km
Pulse repetition rate	300 to 900 pulses per second
Update rate	2 to 5 minutes
Antenna rotation rate	Commensurate with update rate
Processing equipment	Commensurate with real-time display of reflectivity and Doppler attributes individually and collectively

5.1 Range Coverage

The radar must be able to detect reliably the weakest phenomenon of interest over the entire terminal area. Among the phenomena that affect terminal flight safety, the weakest from the point of view of radar detection is the low-level wind shear without precipitation. As mentioned before, refractivity irregularities are much weaker scatterers than particulate tracers, making the detection of clear-air convection more difficult than that of precipitation. Thus, detection of clear-air wind shear sets the range limit on a hazard detection radar. Of some concern is, also, the minimum range of the radar, which is determined by the following three major factors:

i) recovery time of the receiver (and/or duplexer) following the transmitted pulse.

ii) distance to which ground clutter returns received via main and sidelobes of the antenna pattern saturate the receiver.

iii) distance to which the part of transmitter phase noise reflected by the ground clutter is strong enough to interfere with the weather signal.

For modern radars with very low recovery times, the minimum range is usually decided by factor ii) for strongly scattering weather phenomena and by iii) for weak ones.

5.2 Altitude Coverage

The radar must be able to cover the entire altitude interval between the highest, stipulated to be 20,000 ft. (6.1 km) above MSL, and the lowest at which hazardous phenomena may be found. Covering the higher altitudes seldom poses any problem. Again, the lowest height to be observed is determined by low-level wind shear which often has a peak below 500 meters. To detect most parts of a gust front with a peak velocity located at, say, 300 meters altitude, the radar must be able to "look" down to about 100 meters or, preferably, 50 meters. The minimum observable height is determined by the radar horizon (Fig. 4), surface obstructions and ground clutter, in addition to range from the radar. The fact that the phenomenon which decides the minimum height is also the weakest, complicates the problem of hazard detection.

5.3 Range Ambiguities and Overlaid Echoes

The problem of range and/or velocity ambiguities (aliasing) is inherent in pulsed-Doppler systems and in the case of pulsed Doppler weather radars such as NEXRAD, the problem is very real. There is a trade off between choices of unambiguous range and velocity defined in:

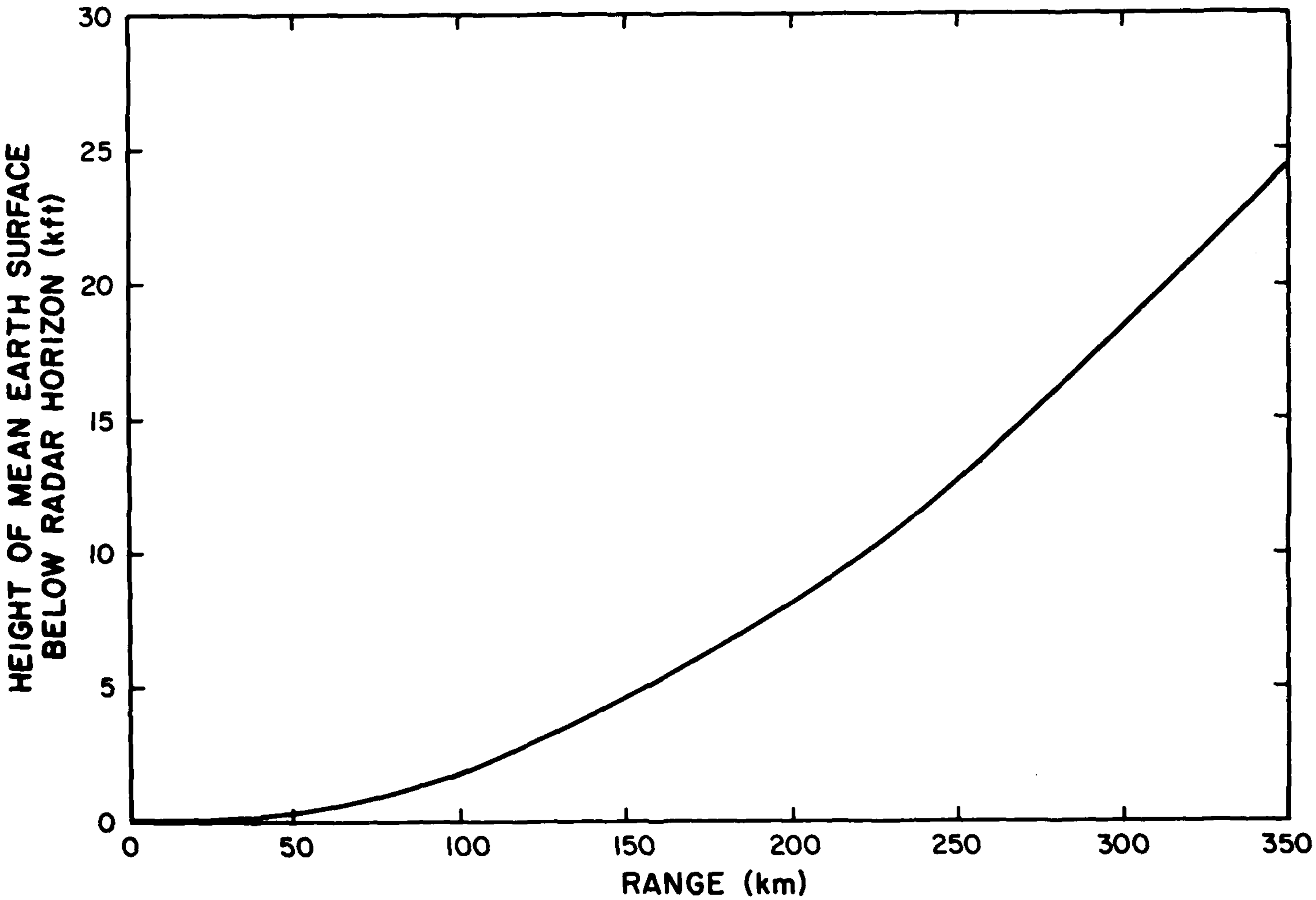

Figure 4 *Vertical distance between a point on the mean earth surface and the radar beam axis (elevation = 0°) as a function of range (using standard 4/3 radius earth model.*

$$r_a v_a = c\lambda/8 \tag{1}$$

where r_a = unambiguous range of the radar

v_a = unambiguous velocity along a radial from the radar

c = propagation speed, 3×10^8 m/sec

λ = radar wavelength

Equation (1) is plotted in Fig. 5 for a few commonly used radar wavelengths. If, as given in Table I, a 10-cm wavelength is chosen from the consideration of antenna size, severe weather penetration, etc., equation (1) reduces to

$$r_a v_a = 3750 \tag{2}$$

where r_a is expressed in kilometers and v_a in meters/sec. Equation (2) appears in Fig. 5 as a bold line. To observe most severe weather phenomena without undue velocity aliasing, an unambiguous velocity up to $\pm30\ \mathrm{m\cdot s^{-1}}$ must be used. Then, relation (2) gives an unambiguous range of 125 km. NEXRAD requirements[29] stipulate a range of 230 km for velocity and spectrum width measurement. Thus, the NEXRAD must have coherent measurement capability over a two-pulse interval.

Although an unambiguous range of 125 km seems large compared to the 56 km radius of the terminal area, the problem of overlaying of features can, nevertheless, be quite serious in the context of terminal area surveillance because of the extremely large dynamic range of the phenomena of interest. Also, unlike point targets such as aircraft and ships, for which the strength of the return signal decreases as the fourth power of range, the return from weather phenomena diminishes only as the square of the range. Thus, if precipitation of strength 40 dBZ* (which is quite common), is occurring at a range of 175 km, it will be folded over and appear as a patch of strength 29 dBZ located at 50 km which is less than the radius of the terminal area. This apparent feature can completely overshadow all clear-air phenomena coinciding with it, including severe low-level wind shear, which usually have reflectivities of the order of 10 dBZ or less. Fig. 6 shows the attenuation of second and third trip weather targets with respect to first trip targets when the unambiguous range is 125 km.

5.4 Zone of Blindess

A radar system is blind to a volume of space directly above it, depending on its scanning scheme. If e_{max} is the elevation angle of the highest level of scan

*The radar reflectivity factor Z is the average sum of the sixth powers of particle diameter per unit volume. It is customary to express Z in units of mm^6/m^3 and then convert it to the decibel system, resulting in the dBZ notation.

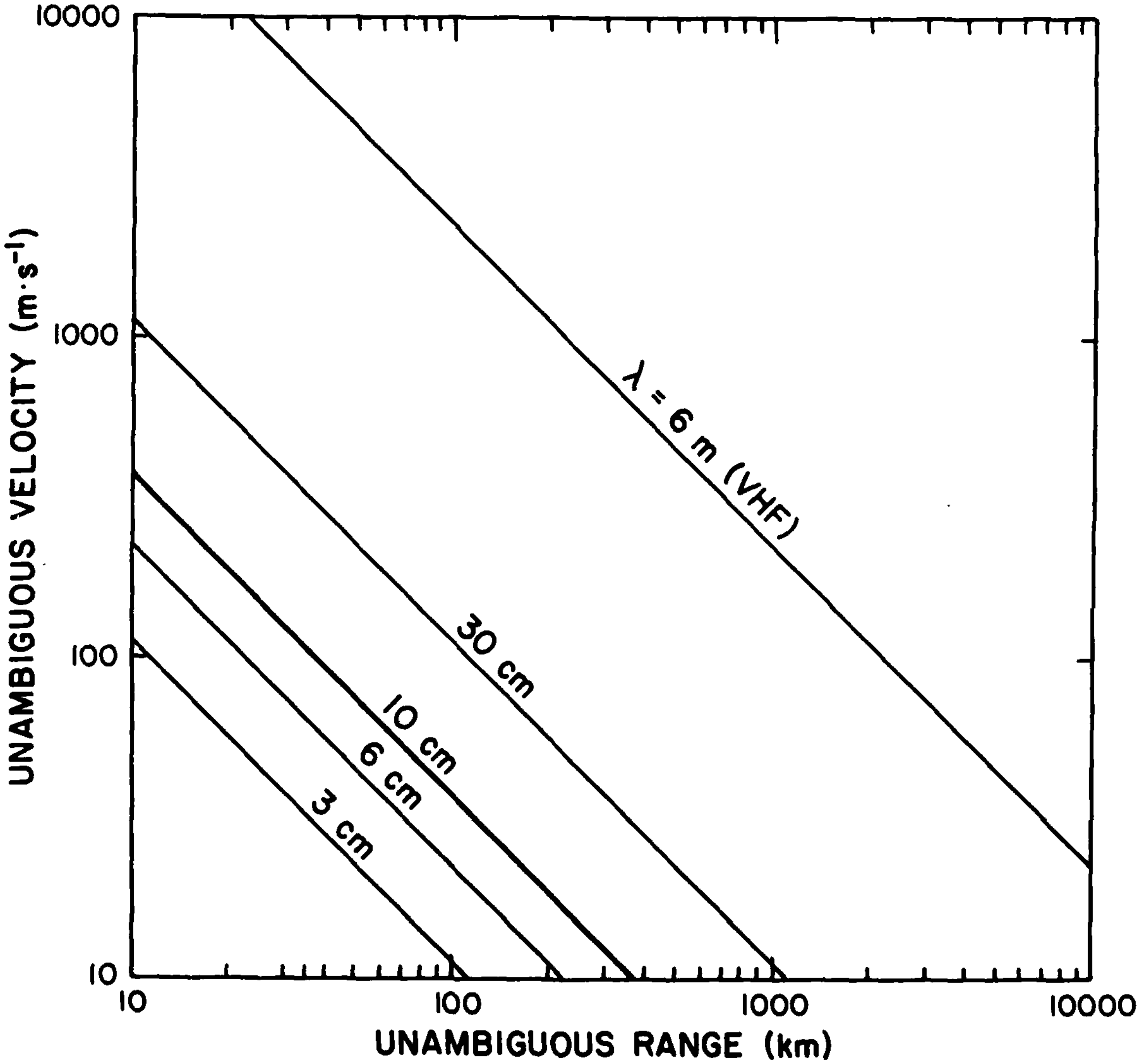

Figure 5 *Plot of unambiguous velocity (i.e., half the total Nyquist interval) vs. unambiguous range for selected radar wavelengths. The 10-cm line, corresponding approximately to NSSL Doppler radar and the proposed NEXRAD is emphasized.*

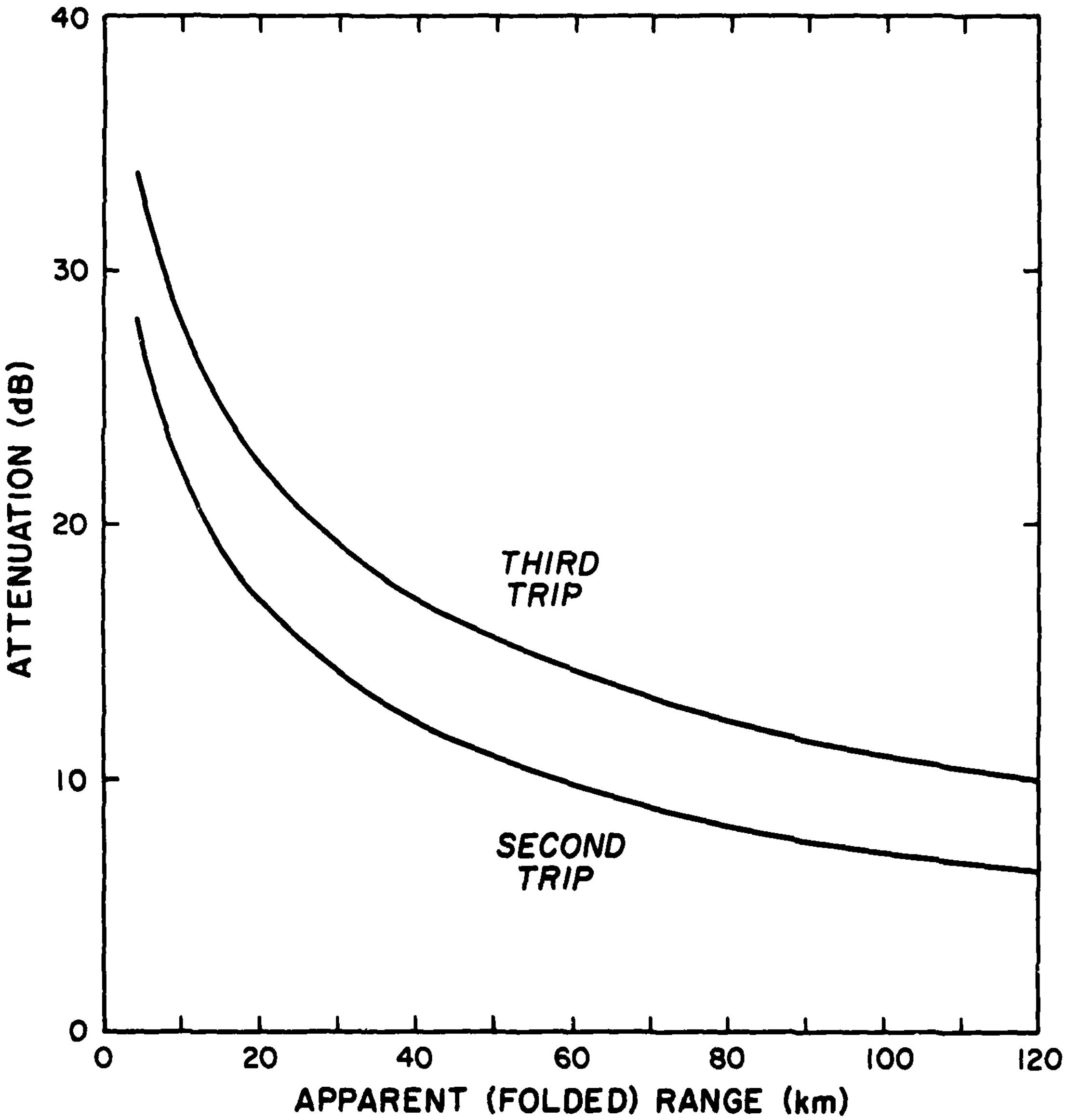

Figure 6 *Attenuation of second and third trip weather targets with respect to first trip targets.*

in degrees, then the overhead blind zone is an inverted vertical cone with a semi-vertical angle of $90-e_{max}$ degrees and vertex located at the radar, as shown in Fig. 7. When the radar is required to observe only up to a specified height, the maximum radius r_b of the overhead blind zone is given as

$$r_b = H \text{ ctn } e_{max} \tag{3}$$

where H is the maximum height of observation.

Studies have been conducted at NSSL on the lifetime and spatial extent of significant storm features and their influence on a scan strategy for NEXRAD[30]. It appears that, as a good figure of compromise between excessive scan time and too large a blind zone, the highest scan elevation should be about 25 degrees. Substituting this value for e_{max} and the stipulated height of 20,000 ft. (6.1 km) for H in (3), the maximum radius of the blind zone is obtained as 13 km.

To decrease the blind zone, the elevation of the highest scan level must be raised further. However, since the scan time increases in proportion with the maximum elevation angle (keeping the spacing between scan levels fixed), this would amount to a considerable reduction in information update rate in exchange for only a modest increase in the scan volume. In the NEXRAD context, where a case exists for actually speeding up data update, any increase in scan cycle time may not be acceptable. Thus, any siting scheme must take into account the existence of a blind zone of maximum diameter of 26 km centered at the radar.

5.5 Resolution

In general, it may be said that the resolution requirement of terminal area weather radars must be finer than en route radars since terminal airspace is more crowded than en route airspace, and also because large trajectory deviations may not be permissible for an aircraft close to takeoff or landing. However, for observing large features such as thunderstorms, an overly fine resolution is not necessary, since, in any case, aircraft must be sufficiently separated from the storm to take into account its gradual edge definition as well as its motion between successive scan cycles of the radar. The radar resolution need not be much finer than this separation.

Considerations are, however, different with regard to the observation of phenomena of smaller spatial extent. For example, in the case of low-level wind shear occurring within a height of 500 meters or less, a linear beam width of

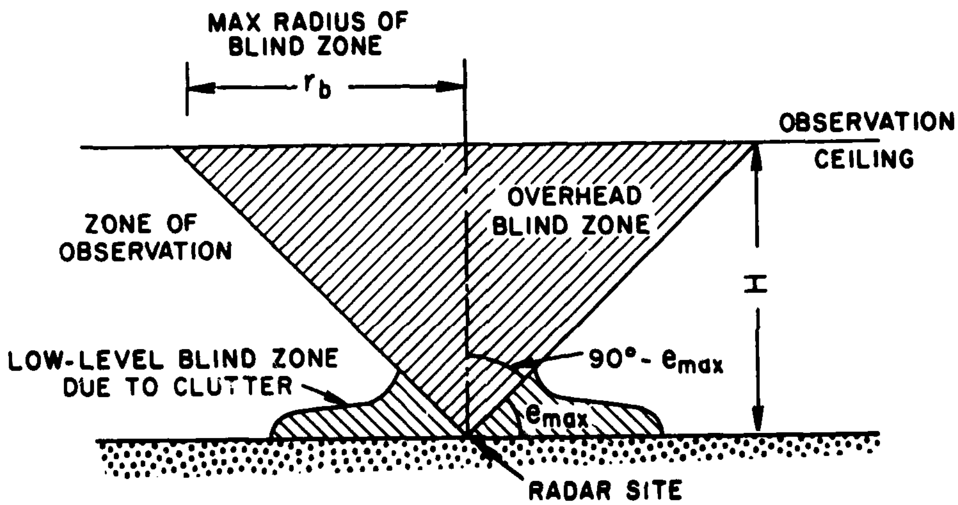

Figure 7 Schematic geometry of radar blind zone.

the order of 200 meters should be used so that the lowest two or three scans of the scan cycle would pass through the part of the shear layer above the radar horizon. With a 1-degree beam (Table I), this means that the radar should not be located more than about 12 km from the point where the existence of a shear layer is to be determined. It is clear that this requirement conflicts directly with the blind zone consideration and that either one of these or both would have to be compromised.

5.6 Information Updating Interval

New information concerning the weather situation within the scan volume is obtained once every scan cycle. The scan cycle time currently being considered for NEXRAD is 5 minutes. The Federal Aviation Administration is exploring the possibility of cutting down the cycle time by a half -- to 2.5 minutes in case there are fast-growing hazardous phenomena that may be missed by using a slower scan rate. One way of achieving this is to locate the radar at some distance from the area surveyed so that scanning of a limited azimuthal sector gives the desired coverage. In such a case, the cycle time can be brought down to 2.5 minutes or less, while scanning all the levels of interest, at the penalty of coarser resolution and higher radar horizon.

There are other possible approaches to the problem of missed detection of short-lived or fast-growing phenomena. These include scanning alternate elevation angles in alternate scan cycles (the so-called "interlaced scanning"), interposing a decimated scan cycle (covering one or a few of the more important levels) within a full scan cycle, etc. Each approach has its own strong points. The sector scan has the advantage that the maximum time interval between data update at any level in a scan cycle is a minimum, if the total number of scan levels is kept the same in all approaches.

5.7 Other Functions

Although the present discussion concerns the use of NEXRAD for terminal area surveillance, it must be remembered that the NEXRAD system is not being designed solely for this pupose, but with a much wider application in mind. In fact, it is expected to eventually replace the current generation of non-Doppler radars for routine weather coverage as well as en route air weather monitoring over most of the conterminous U.S. (CONUS). Thus the terminal area surveillance function of the NEXRAD should not conflict seriously with its broader role as a weather radar.

6. Discussion of Specific Siting Alternatives

Depending on the distance of the NEXRAD site from the runway complex, three broad siting alternatives are considered: a) airport area, b) air terminal area, and c) outside the air terminal area. The relative merits and demerits of each of these alternatives are discussed below:

6.1 Siting in Airport Area

Airport area is defined as an area of 10.8 nmi (20 km) radius about the runway complex. Locating a NEXRAD radar within this area offers several advantages:

1. Since the detectability of a weather feature improves as R^{-2} (R = range from radar), a closer location helps the detection of weakly scattering phenomena, such as those occurring in clear air, over the runway complex.

2. Observation at close range minimizes the probability of overlaid echoes from strong features obscuring weak scatterers. This is so because multiple-trip echoes are attenuated by the square of the ratio between the actual and apparent (ambiguous) ranges. Thus, if a weak feature lies at a range of 10 km and a strong feature at 135 km folds over it (unambiguous range = 125 km), then the strong feature will be attenuated by a factor $(135/10)^2 = 182$, or 23 dB (see also Fig. 6) and, hence, it will have less chance of overpowering the weak feature.

3. Because of the above two reasons, close siting provides measurement of vertical profile of wind shear where it is most needed -- on the runways and the parts of glideslopes closest to runways.

4. Since linear beam width is small at close ranges, airport siting provides excellent resolution for mapping wind shear phenomena along critically important glideslope approaches to runways.

5. Problems of beam blockage may not be severe because tall buildings would not be allowed close to the airport.

6. Since the stipulated ceiling height of radar observation is the smallest (10 kft or 3.05 km)[28,29] in the airport area, the maximum radius of the blind zone is also the smallest, as seen from equation (3).

The disadvantages of siting NEXRAD in the airport area include:

1. Loss of flexibility in locating a site, since most parts of the airport area are occupied by runways, airport structures and accessories.

Also, the radar installation itself would be subject to height restrictions within the airport area.

2. Although the overhead blind zone is the smallest, it is located in a more critical area close to the runway complex.

3. Requirement for sophisticated clutter rejection techniques. Ground clutter is the most difficult problem encountered in performing close-range observation of weather phenomena. At low elevation angles (less than 3-dB beamwidth), the main beam of the antenna pattern is responsible for most of the clutter return while at higher elevation, clutter is caused primarily by sidelobe returns. Thus, at low elevation angles, clutter is more severe. In the NSSL experimental Doppler weather radar at Norman, Oklahoma, the average range of severe clutter interference is about 15 to 20 km for an elevation angle of 0.5 degree and is about 5 km when the elevation is of the order of 2 degrees or more. It would be possible to reduce the latter figure by using an improved antenna in the NEXRAD with lower sidelobe level (one-way mainlobe-to-sidelobe ratio of 25 dB may be adequate) and by improving the radome design and construction to minimize the distortion of the basic antenna pattern. A reduced sidelobe level has the added advantage that strongly reflecting precipitation appearing in the sidelobes would have less interfering effect on the main beam observation of weather targets.

The problem of main beam clutter, however, cannot be solved by antenna and radome improvements. This problem is especially severe while trying to observe the lowest levels stipulated by FAA for the airport area; this level is at 200 ft (61 m) above ground[31]. If the radar is to be located 10 km away from the center of the runway complex, the opposite end of the airport area would be 30 km away and to observe a height of 61 m, the elevation angle of the lower 3-dB point of the beam should be 0.12 degrees. At this elevation angle, main lobe ground clutter can extend to over 30 km in range. By using relatively simple and affordable clutter filtering techniques, the area of severe ground clutter interference can be considerably reduced, but this would impose some constraints on the number of pulses that must be available for processing (which, in turn, regulates the scan rate) and discourage the use of nonuniform pulse spacing for range de-aliasing[32,33].

A very effective, but relatively expensive method of clutter filtering in the reflectivity field is to generate and store a static clutter map of

the area around the radar installation and subtract the clutter strength, cell by cell, from the incoming signal. However, a static clutter map has the drawback that if the clutter environment changes with time (as it often does) then cancellation performance will be degraded. A way out of this problem is to use a dynamic mapping scheme in which the clutter map is continuously updated, based on the near-zero frequency component of the most recent observations, but this method again has the disadvantage that stationary or nearly stationary weather phenomena are recognized erroneously as clutter and are included in the clutter map[17].

The success of any clutter rejection scheme at all is based on the assumption that clutter and weather signals appear additively at the receiver output which is true only if the receiver operates in the linear region. When the clutter return is so strong that the receiver is saturated, the weather signal component is irrecoverably lost and no clutter cancellation method can retrieve that signal. Although the range at which saturation occurs is a function of several radar and clutter parameters, based on experience with NSSL radars, a probable figure under the NEXRAD operating conditions lies between 2 and 5 km. The minimum range based on ground return of transmitter noise, as explained before, is probably higher. If convective phenomena are to be observed at closer ranges, then receiver de-saturation methods such as sensitivity-time control (STC) must be employed, along with the attendant complications of hardware and software.

It is thus clear that there is no easy way out of the problem of main beam clutter and that sophisticated clutter cancellation methods are necessary for successful observation of low-level wind shear at close ranges. The minimum distance of the radar from the runways is obtained from blind zone considerations. Fig. 8 shows the minimum and maximum altitudes of weather radar coverage in different areas, as required by FAA. For a maximum altitude of 10,000 ft. (3.05 km) and a maximum scan elevation of 25°, the radius of the overhead blind zone is obtained from equation (3) as 6.5 km. Thus, to observe the space directly above and in the immediate vicinity of runways and glideslopes, the radar should not be located closer than about 8 km (preferably 10 km) from the nearest runway or glideslope. However, at the altitude of low-level wind shear phenomena (approx. 500 m) the radius of the blind zone is very small and it may be assumed that the radar can 'see' these phenomena over the entire airport area.

6.2 Siting in Terminal Area

Locating the NEXRAD radar within the terminal area (30 nmi or 56 km radius), but outside the airport area (10.8 nmi or 20 km radius), offers the following advantages:

1. The runway complex as well as the critical parts of the glideslopes, where weather observation is of utmost importance, are well outside the range of sidelobe ground clutter. Also, main lobe ground clutter would not be a serious problem in observing these critical areas since they are at a minimum range of about 20 km, and since these areas would return relatively less clutter because of the flatness of terrain and absence of significant man-made structures in the vicinity of the runway complex.

2. By suitably locating the radar, the entire airport area can be kept outside the blind zone of the radar.

3. A greater flexibility in siting the radar is obtained so that coverage can be optimized. This may include minimizing beam blockage from buildings, raised ground or mountains, etc., and close-range coverage of other nearby installations.

4. By locating the radar close to the airport area boundary (within 21 km from the center of the runway complex for a 1° beam) the stipulated resolution of 365 meters[31] can be obtained over the runway complex.

5. Obscuration of the terminal area due to multiple trip echoes from thunderstorm squall lines[33] can be reduced by locating the radar so that the line joining the radar and the runway complex is perpendicular to the most frequently observed orientation of the squall lines in the area.

The chief disadvantages of locating the NEXRAD radar inside the terminal area but outside the airport area are:

1. Since the stipulated ceiling height of observation for the terminal area (20 kft MSL) is more than that for the airport area (10 kft AGL)[31], the maximum diameter of the overhead blind zone would be correspondingly larger for the former. The maximum diameter of the blind zone has a radius of 13 km for the terminal area as compared to 6.5 km for the airport area. This assumes that the airport being considered does not have an appreciable height above the mean sea level.

2. To satisfy the minimum altitude coverage requirement all over the airport area, the beam would have to graze the ground at close ranges.

Thus, the severe main beam clutter problems mentioned earlier would remain in their entirety. However, because of the relatively distant location of the radar, the runway complex and glideslopes will be outside the zone of strong clutter interference.

With a relatively modest clutter cancellation scheme, the zone of severe clutter interference can be made smaller than the overhead blind zone of the radar. This does not, however, mean that the incentive for further clutter cancellation is lost. The maximum radius of the overhead blind zone is defined only at the highest level. At lower levels, the area of the blind zone gets progressively smaller, and at the height of low-level wind shear, it is negligibly small. Thus, any improvement in clutter performance will result in better coverage close to the radar. Also, to avoid surprise developments within the blind zone of a radar, the zone must be observed, albeit coarsely, by an adjacent NEXRAD system. Since such a system is likely to be far away (as much as 400 km), it can observe only the top part of the next radar's blind zone, the bottom part being below its radar horizon. Thus, there is no redundancy available in the observation of low-level phenomena and, hence, reduction in clutter is the only way that low-level phenomena close to the NEXRAD site can be observed.

In relative terms, however, the clutter performance of a NEXRAD located in the terminal area need not be so stringent as that of one located within the airport area. This is because it is possible to choose a location within the terminal area where very low-level aircraft flights do not occur. A low-level wind shear phenomenon, such as a gust front, is likely to be wide enough to have detectable portions outside the clutter region. If it is small enough to be entirely in the clutter zone, it would be detected at a later time as it gets out of that zone and moves toward the runway area where it can be a source of hazard.

3. If the radar is assumed to be located at a distance of 38 km from the runway area (halfway between the boundaries of airport and terminal areas) then, with a 1-degree beam, the worst resolution within the airport area would be 1000 meters and within the terminal area it would be 1600 meters. This is much worse than the FAA stipulated values of 365 and 1000 meters in those areas respectively[31].

6.3 Siting Outside Terminal Area

A NEXRAD radar can also be located outside the terminal area, i.e., at a distance greater than 56 km from the center of the runway complex. Such a location has several advantages:

1. It offers the possibility of covering the terminal area by sector scan, rather than full-circle scan. Since the scan cycle time varies almost in proportion with the angular width of the sector being scanned, the information updating interval can be reduced in this manner. This would minimize the possibility of fast-evolving phenomena growing to hazardous levels between successive scan cycles of the radar. Such a possibility has been the cause of some concern on the part of FAA which has favored a somewhat faster scan rate than the 5 minutes nominally accepted for NEXRAD and has instituted some studies in this connection[30,34]. The sector-scan advantage of locating the NEXRAD outside the terminal area may not, however, be realizable in practice because of other commitments of the system, such as en route surveillance and general weather monitoring, which may enforce a full-circle scan pattern.

2. The greatest flexibility in siting is obtained because the requirement of terminal area surveillance does not seriously interfere with plans to set up a nationwide network of NEXRAD radars. Studies have been conducted[29] to evolve a siting scheme for optimally covering the CONUS, using a minimum number of radars. Such coverage will be facilitated if the NEXRAD is not constrained to be located within the terminal area.

3. The entire terminal area can be made to lie outside the clutter region and the blind zone of the radar. Thus, complete coverage of the terminal area can be obtained and expensive clutter-filtering methods need not be employed.

The following are the disadvantages of locating the NEXRAD outside the terminal area:

1. The stipulated minimum altitude of observation over the airport area falls below the radar horizon even when the radar is located close to the terminal area boundary. Thus, when the radar is close to the ground level at about 20 km from the terminal area boundary, the height of the radar horizon above ground at the runway complex is about 1000 ft (305 m), rather than the stipulated minimum of 200 ft (61 m). Visibility may be

improved by installing the radar higher above the ground, but this would have the drawback of increasing the range of clutter interference since the shielding provided by the ground at close range (causing faster main beam rolloff) would be lost.

2. The resolution requirements would not be satisfied. Assuming the radar to be 76 km away from the center of the terminal area (20 km from the boundary) and a 1° beam width, the worst resolution in the airport and terminal areas would be 1700 meters and 2300 meters, respectively. As mentioned before, the stipulated resolutions in these areas are 365 and 1000 meters, respectively (Fig. 8).

3. The distance of the radar from the runway area would be limited by the range to detect low-level wind shear. Experiments at NSSL show that observation of clear air phenomena of moderate strength (of the order of 10 dBZ) within the planetary boundary layer is reliable only up to about 60 km.

4. The interference due to overlaid echoes is stronger than that for a radar located in the airport area.

7. Comparison of Siting Alternatives

It is clear from the foregoing discussions that no single siting option satisfied all the FAA requirements of weather surveillance over the entire terminal area. The problem of optimal siting therefore reduces to choosing a location that minimizes the compromises.

Resolution requirements over the entire terminal area can be met only by locating the radar very close to (within about 1 km) the center of the terminal area. This condition, together with the advantages of close observation of runways and terminal parts of glideslopes, and minimum risk of range-folded overlay are strong factors favoring location of the NEXRAD radar within the terminal area. The existence of an overhead blind zone and a clutter-limited area close to critical areas,such as runways and glideslopes, is a strong reason against airport area location.

Locating the radar outside the airport area, whether within or outside the terminal area boundary, violates the resolution requirement. However, these sites offer the important advantage of nearly clutter-free operation over the runway complex which is the main area of interest. In addition, siting outside the terminal area makes possible complete coverage of the terminal area without any blind zone.

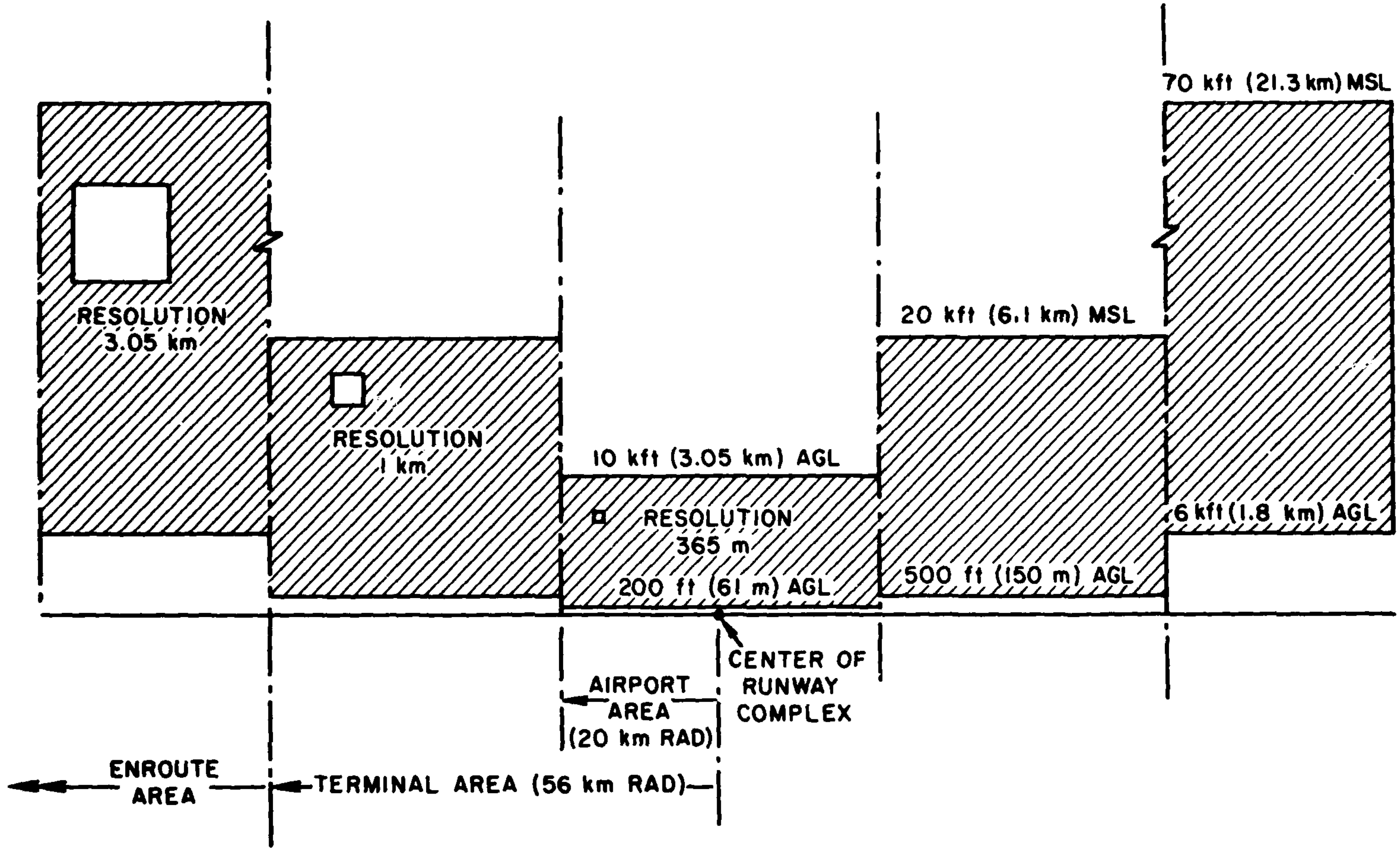

Figure 8 *FAA requirements*[28] *of altitude limits and resolution for NEXRAD coverage in different flight areas* (AGL: *Above Ground Level,* MSL: *Mean sea Level,* RAD: *Radius).*

Overall, it appears that if one NEXRAD radar is required to observe all hazardous convective phenomena over the entire terminal area, then it has to be located within the airport area. A preferred range of location would be between 10 and 12 km from the center of the runway complex. Also, a minimum distance of about 8 km must be maintained from the nearest runway or glide-slope. With such a location, the blind zone and the clutter area can be kept clear of runways and glideslopes.

It should be remembered, however, that when a radar is located at a range of, say, 10 km from the center of the runway complex, it may be only about 6 or 7 km from the nearest runway and to keep this runway and its vicinity positively clear of clutter, the clutter zone must be limited to about 5 km in range. This approaches the range at which clutter starts saturating the receiver, and clutter-reflected transmitter noise would also severely compete with weather signal at such ranges. Thus, the suggested location still requires efficient anti-clutter measures for satisfactory operation. In addition to using transmitters with very good phase stability, signal processing or beam shaping or both may be employed. The former consists of the spectral or time-domain filtering, static or dynamic clutter map generation and subtraction, and sensitivity-time control methods mentioned earlier. The latter may involve antenna shrouds for sidelobe reduction and "clutter fences" which are RF screens erected around the radar installation to provide artificial blockage of the ground-grazing parts of the main beam and thus reduce backscatter from points on the ground beyond the fence. The clutter fence, in effect, causes a faster rolloff of the lower side of the main beam radiation pattern at far field than what is provided by the antenna.

It must be pointed out here that the location of the NEXRAD as suggested above would somewhat violate the resolution requirement in the terminal and airport areas. The worst resolution in the airport area would be 520 meters as against a stipulated 365 meters, and in the terminal area it would be 1150 meters as against 1000 meters. To fully satisfy resolution requirements from the proposed location in the terminal area, a beam width of 0.7 degrees would have to be employed. In addition to nearly doubling the aperture area of the antenna, it would slow down the scan rate for a given processing time and the scan cycle time of 5 minutes would be more difficult to achieve. If beam blurring due to antenna rotation is taken into account, a static beam width of about 0.5 degrees may have to be adopted to satisfy the resolution requirements. This would escalate the cost of the radar system rather steeply.

It appears that the resolution requirements of FAA are too stringent and may have to be relaxed at least at the edges of the regions concerned. One suggestion is not to specify constant values of resolution over entire areas, but to express resolution as an increasing function (linear or parabolic, say) of radial distance from the center of the runway complex, subject to a ceiling. This would also make the stipulated resolution continuous across the boundaries of the airport and terminal areas, which appears to be a natural thing to do. A suggested resolution law is

$$\Delta r = \min\left[(350 + 0.45\, r^2),\ 3050\right] \tag{4}$$

where Δr in meters is the required resolution at a distance r(km) from the center of the runway complex. This law guarantees a resolution of 365 meters over the runway complex and 1000 meters at 38 km which is midway between the airport and terminal area boundaries. Fig. 9 shows the resolution scheme given by equation (4) superimposed on the currently stipulated resolution specifications. The suggested radar location 10 km from the center of a runway complex would satisfy the resolution given by (4) with a 1-degree beam.

In the case of very large and busy airports, a case exists for siting the radar outside the terminal area. This is because a suitable place may not be available in the 10-12 km range interval suggested earlier and, more importantly, such a location offers the possibility of sector scanning, resulting in a faster data update rate. Although a NEXRAD unit tied to the national weather network is most likely to have a full-circular scan pattern, the scale of operations at a large airport may justify the use of a dedicated NEXRAD unit which may then operate in a manner most optimum for terminal area surveillance, without any compromises dictated by other applications.

The use of other instrumentation to aid NEXRAD operation has been mentioned in literature. Strauch and Sweezy[20] have suggested distributed wind shear sensors, consisting of small antennas and low-power transmitters with receivers located at the intersection of major runways and hooked to a common data system. Such a system would complement the NEXRAD system, which would then be primarily used for storm surveillance. However, in its simplest form, it will be effective only in the presence of precipitation[20]. To detect wind shear in clear air, each of these instruments would have to be a nearly complete radar unit of considerable

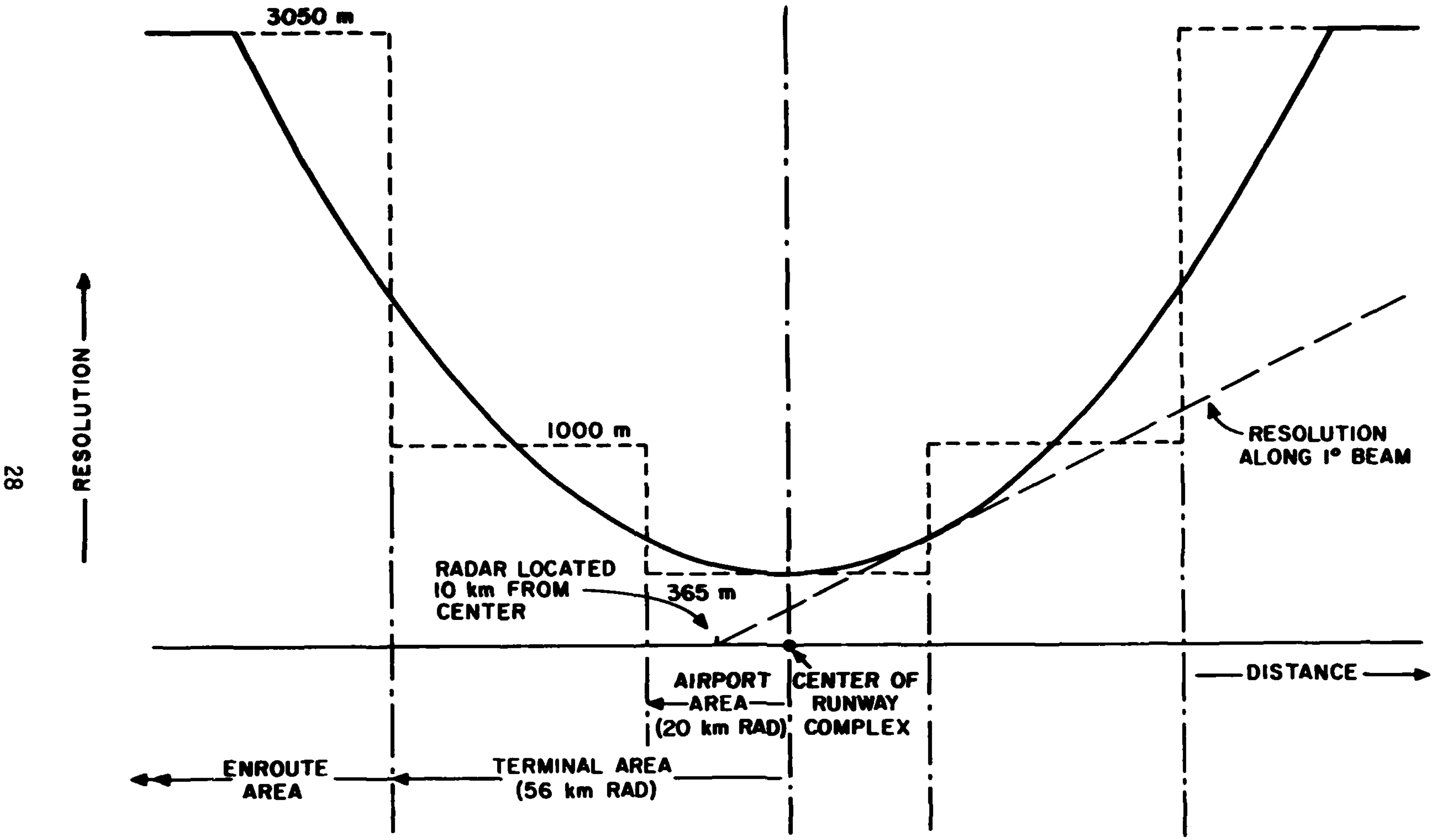

Figure 9 *Suggested parabolic resolution law shown superimposed on the currently stipulated stepwise resolution scheme. Note that a radar offset 10 km from the center and having a 1° beam would satisfy the smooth resolution requirement, whereas it somewhat violates the stepped scheme* (RAD: *Radius*).

sophistication, resulting in high cost. While work toward proving the feasibility and economics of such a proposal is worthwhile, the best course for an operational system at present is to extract as much detection capability as possible from a general system such as NEXRAD by suitable parameter design and siting.

8. Concluding Remarks

The decision regarding siting a radar for the detection of hazardous convective phenomena in the terminal area around a particular airport depends on a large number of factors among which are the topography and layout of the airport, type, distribution and severity of the convective phenomena normally encountered in that area, characteristics of the radar to be sited and the totality of functions assigned to the radar. In the absence of detailed information on all of these, the discussion can at best be a general one, based on average parameters. There is much interplay of the various significant factors involved in choosing a proper site for a NEXRAD radar for terminal area surveillance.

The parameters of the NEXRAD system are still in a stage of evolution and are not yet available in a final form. One of the objectives of the study reported in this paper is to help finalize the NEXRAD system parameters by pointing out cases where the proposed parameters either conflict with, or are inadequate for, one of the proposed functions of the NEXRAD system -- terminal area hazard surveillance.

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